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Remote sensing i~ and diffuse reflection R coefficients of seawater are dependent on inherent optical properties of seawater through the Gordon's parameter bB / (a bB), where a is an absorption and b is backscattering coefficients. g =+B Majority of researchers in ocean optics use linear approximation for ~ and R, i. e. ~g and R oc g. This approach works well when g ~ 0.1. All open and largest part of coastal waters satisfy this condition, but there are some cases when parameter g is as large as 0.98. We illustrate this fact with a histogram of Gordon's parameter g for the Yellow sea waters. We present a choice of alternative rigorous nonlinear equations for R that solve this problem, i.e. significantly reduce the error of the restoration of the Gordon's parameter g from remote sensing optical data and .estimate possible errors in using linear dependencies

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ABOUT NONLINEAR DEPENDENCE OF REMOTE SENSING AND DIFFUSE REFLECTION COEFFICIENTS ON GORDON'S PARAMETER

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Abstract: Remote sensing r_{rs} and diffuse reflection R coefficients of seawater are dependent on inherent optical properties of seawater through the Gordon's parameter $g = b_B / (a + b_B)$, where a is an absorption, and b_B is backscattering coefficients. Majority of researchers in ocean optics use linear approximation for r_{rs} and R, *i. e.* $r_{rs} \propto g$ and $R \propto g$. This approach works well when $g \leq 0.1$. All open and largest part of coastal waters satisfy this condition, but there are some cases when parameter g is as large as 0.98. We illustrate this fact with a histogram of Gordon's parameter g for the Yellow sea waters. We present a choice of alternative rigorous nonlinear equations for R that solve this problem, *i.e.* significantly reduce the error of the restoration of the Gordon's parameter g from remote sensing optical data and .estimate possible errors in using linear dependencies

1. Introduction

Diffuse reflection coefficient (DRC) of water body is an informative part of remote sensing reflectance [1] of light by the ocean. DRC contains information on content of dissolved and suspended substances in seawater. DRC is an apparent optical property that depends not only on inherent optical properties of the seawater, but also on the parameters of illumination. The dependence on inherent optical properties is expressed through the dependence on Gordon's parameter, *i.e.* the ratio of backscattering coefficient b_B to the sum of absorption a and backscattering coefficient, $g = b_B / (a + b_B)$. In the open ocean DRC is linearly proportional to g. This linear equation is very good for the Type I open ocean waters [2]. It is also acceptable for about 90% of coastal waters. Theoretical and numerical analysis show that the linear relationship can be adequately used only when Gordon's parameter g is relatively small, *i.e.* $g < 0.1$. This criterion is always satisfied in open ocean waters. The available database of experimental measurements show that in coastal waters Gordon's parameter may exceed this critical value of 0.1. In some very turbid coastal waters it can even reach values higher than 0.95. For example, in waters of Yellow Sea or coastal waters close to river estuaries the percentage of cases when $g > 0.1$ can reach 50% or more. In this paper we illustrate this fact with a histogram of Gordon's parameter for the Yellow sea waters. We estimate possible errors in using the linear dependence and present a choice of alternative rigorous nonlinear equations for DRC that solve this problem, *i.e.* significantly reduce the error of the restoration of the Gordon's parameter from remote sensing optical data.

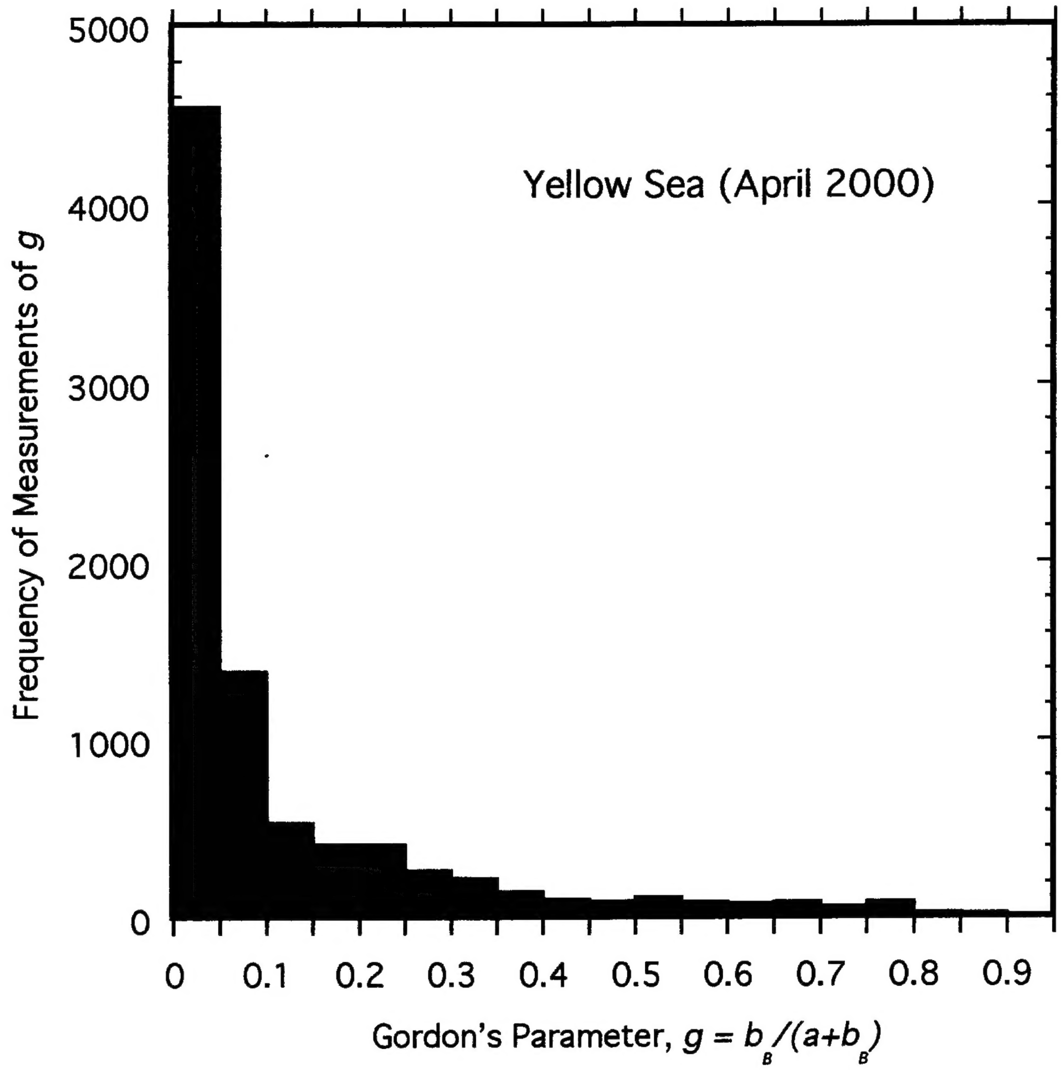

Figure 1. Distribution of occurrences of measured Gordon's parameter in Yellow Sea in 2000.

2. Gordon's parameter in highly scattering marine environment

Until recently we had no significant cases of *in situ* measurements that show existence of sea waters with high cases of Gordon's parameter g exceeding 0.1. Relatively recent measurements made in 2000 by NRL researches with collaboration of Korean scientists in Yellow Sea shows that these highly scattering waters exhibit these characteristics. Figure 1 shows a histogram of the frequency of measurements of Gordon's parameter in this expedition. In this case more than 50% of measurements correspond to Gordon's parameter exceeding critical limit of linear approach. It means that processing of such data should involve nonlinear equations connecting DRC with g.

3. Equations for diffuse reflectance that valid for all values of Gordon's parameter

Fortunately, we have both experimental data and theoretical equations that correctly connect diffuse reflection coefficient with Gordon's parameter g, and, consequently, with a and b_B for the full range of their variability, $0 \le g \le 1$, $0 \le a \le \infty$, $0 \le b_B \le \infty$. First, we have experimental data published by Timofeyeva in 1972 and 1979 [3, 4] (see Tab. 1). Second, we have several equations that connect DRC with g in the full range of variability of this parameter, $0 \le g \le 1$. Let us consider these cases.

Table 1. Optical properties of natural and modeled scattering and absorbing media according to experiments by Timofeyeva. Here $\bar{\mu}$, $\bar{\mu}_d$, and $\bar{\mu}_u$ are, correspondingly, total, downward, and upward average cosines over radiance distribution in the scattering medium [5].

$\bar{\mu}$	$\bar{\mu}_d$	$\bar{\mu}_u$	R	g	R/g
0	0.5	0.5	1.0	1.0	1.0
0.1	0.5249	0.4831	0.671	0.9408	0.7132
0.2	0.5525	0.4545	0.443	0.7970	0.5550
0.3	0.5834	0.4202	0.283	0.6179	0.4580
0.4	0.6184	0.3745	0.171	0.4439	0.3852
0.5	0.6566	0.3311	0.095	0.2959	0.3211
0.6	0.7008	0.3003	0.048	0.1802	0.2664
0.7	0.7536	0.2857	0.0207	0.0967	0.2141
0.8	0.8217	0.3610	0.0082	0.0413	0.1985
0.9	0.9033	0.6849	0.0016	0.0101	0.1584
1.0	1.0	1.0	0.0	0.0	0.25

a) Equation derived from the exact solution of radiative transfer equation in the depth of scattering medium [6]:

$$R = \frac{1-\eta}{1+\eta}\left(\sqrt{1+\eta^2}-\eta\right)^2, \quad \eta = \sqrt{\frac{1-g}{1+(3+2\sqrt{2})\,g}} \equiv \sqrt{\frac{a}{a+2(2+\sqrt{2})b_B}}. \tag{1}$$

b) Equation derived in the framework of self-consistent approach [5] (asymptotic case):

$$R_\infty = \left(\frac{1-\bar{\mu}}{1+\bar{\mu}}\right)^2, \tag{2}$$

$$\bar{\mu} = \sqrt{\frac{1+2g-\sqrt{g\,(4+5\,g)}}{1+g}} \equiv \sqrt{\frac{a}{a+3b_B+\sqrt{b_B\,(4a+9b_B)}}}. \tag{3}$$

c) Equation derived in the framework of self-consistent approach [5] (case of diffuse illumination):

$$R = \frac{2(1-\overline{\mu})^2}{\overline{\mu}(3-\overline{\mu}^2)}\left\{1 - \frac{1+\overline{\mu}^2}{\overline{\mu}(3-\overline{\mu}^2)}\ln\left[1+\frac{\overline{\mu}(3-\overline{\mu}^2)}{1+\overline{\mu}^2}\right]\right\}, \tag{4}$$

here $\overline{\mu}$ is defined by Eq. (3).

d) Equation derived in the framework of semi-empirical approach [7] that is based on experimental data presented in Tab. 1:

$$R \equiv \frac{1-\overline{\mu}/\mu_d}{1+\overline{\mu}/\mu_u}, \tag{5}$$

here

$$\overline{\mu} = a_0 + (1-a_0)\sqrt{1-g} + \sum_{n=1}^{6} a_n g^{\frac{n}{3}}, \tag{6}$$

$$\mu_d = \left[1 - \overline{\mu}(1-\overline{\mu})^2 \sum_{n=0}^{3} b_n \overline{\mu}^{2n}\right] \Big/ (2-\overline{\mu}), \tag{7}$$

$$\mu_u = \left[1 - \overline{\mu}(1-\overline{\mu})^2 \exp\left(\sum_{n=0}^{4} c_n \overline{\mu}^{2n}\right)\right] \Big/ (2-\overline{\mu}). \tag{8}$$

The coefficients a_n, b_n and c_n in Eqs. (5-8) are given in Tab. 2.

Table 2. Coefficients to Eqs. (5)-(8).

n	a_n	b_n	c_n
0	0.5918	0.0326	-0.0131
1	-0.7937	0.1661	8.4423
2	4.8350	0.7785	-15.6605
3	-22.8150	0.0228	21.8820
4	42.6859		-11.2257
5	-35.8945		
6	11.3905		

Equations (1)-(8) are valid for the full range of variability of parameters g, a, and b_B: $0 \le g \le 1$, $0 \le a \le \infty$, $0 \le b_B \le \infty$. In order to make a comparison and estimate possible errors for the case presented in Fig. 1 we will use also the following equation used in ocean optics research:
e) Linear equation by Morel and Prieur [2]:

$$R = g/3. \tag{9}$$

Linear equation (9) was never meant to be used by authors in the full range of variability of g. It was proposed for the case of open ocean waters where g is small.
f) Kubelka-Munk equation [8]:

$$R = \left(1 - \sqrt{1 - g^2}\right)/g. \tag{10}$$

Equation (10) was derived in the assumption that $\bar{\mu}_d = \bar{\mu}_u = 0.5$. Because in seawater both $\bar{\mu}_d$ and $\bar{\mu}_u$ are far from 0.5 (see Tab. 1) that equations is not good for marine optics except special cases with $g > 0.6$.

g) Equation by Gordon *et al.* [9] for directed sun illumination:

$$R = 0.0001 + 0.3244\,g + 0.1425\,g^2 + 0.1308\,g^3,\ \ (0.1 \le g \le 0.5). \tag{11}$$

g) Equation by Gordon *et al.* [9] for diffuse illumination:

$$R = 0.0003 + 0.3687\,g + 0.1802\,g^2 + 0.0740\,g^3,\ \ (0.1 \le g \le 0.5). \tag{12}$$

Dependencies of DRC on Gordon's parameter g computed according to Eqs. (1), (2), (4), (5), and (10)-(12) are shown in Fig. 2. Equations (1), (2), (4), and (5) give quite similar results and are valid for the whole range of $0 \le g \le 1$.

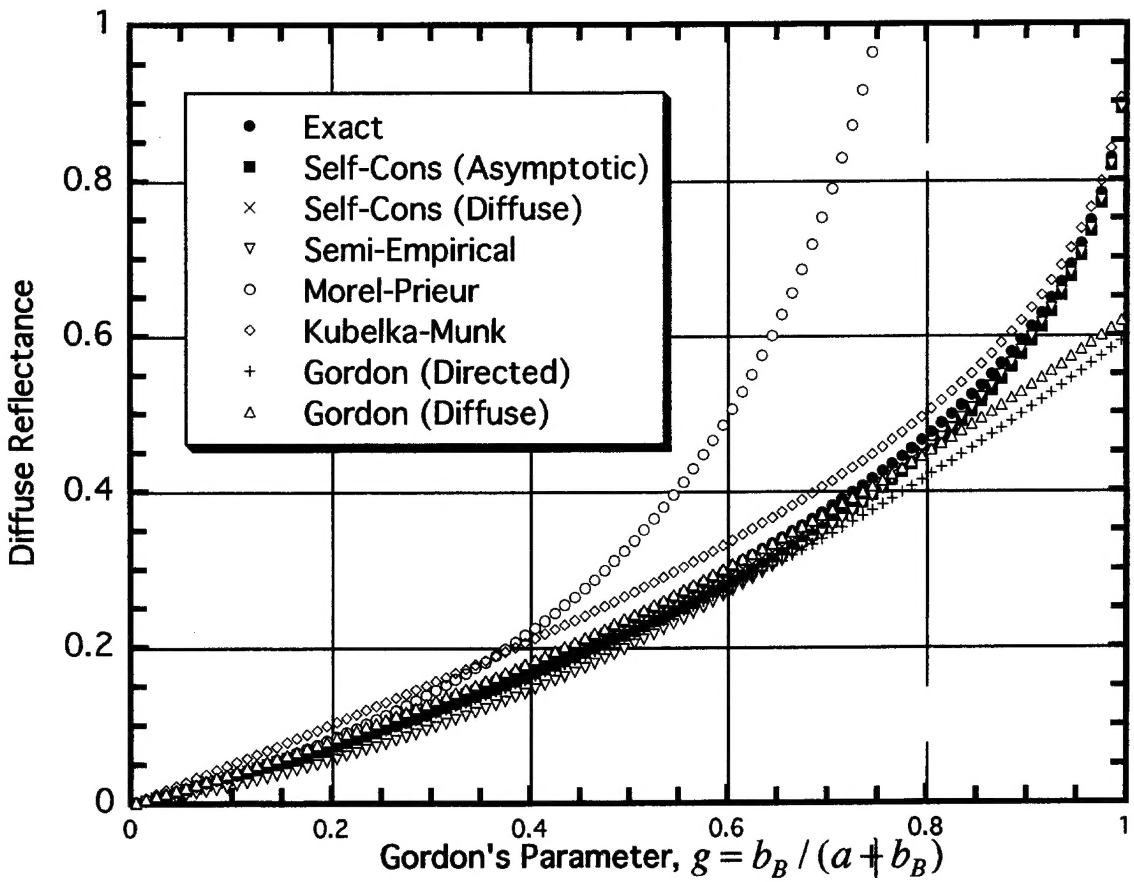

Figure 2. Dependence of Diffuse Reflectance Coefficient Gordon's parameter.

4. Possible errors of using linear equations in highly-scattering waters

In order to estimate possible errors to compute diffuse reflection coefficient as a "precise" reference we used values of R as a function of g generated numerically by Hydrolight [10, 11] for the case of diffuse illumination of sea surface. The error distributions for Eqs. (2), (4), (5), and (10)-(12) are shown in Fig. 3. Because the errors of Eq. (1) for the case of diffuse illumination is much smaller, we omitted its dependence from Fig. 3.

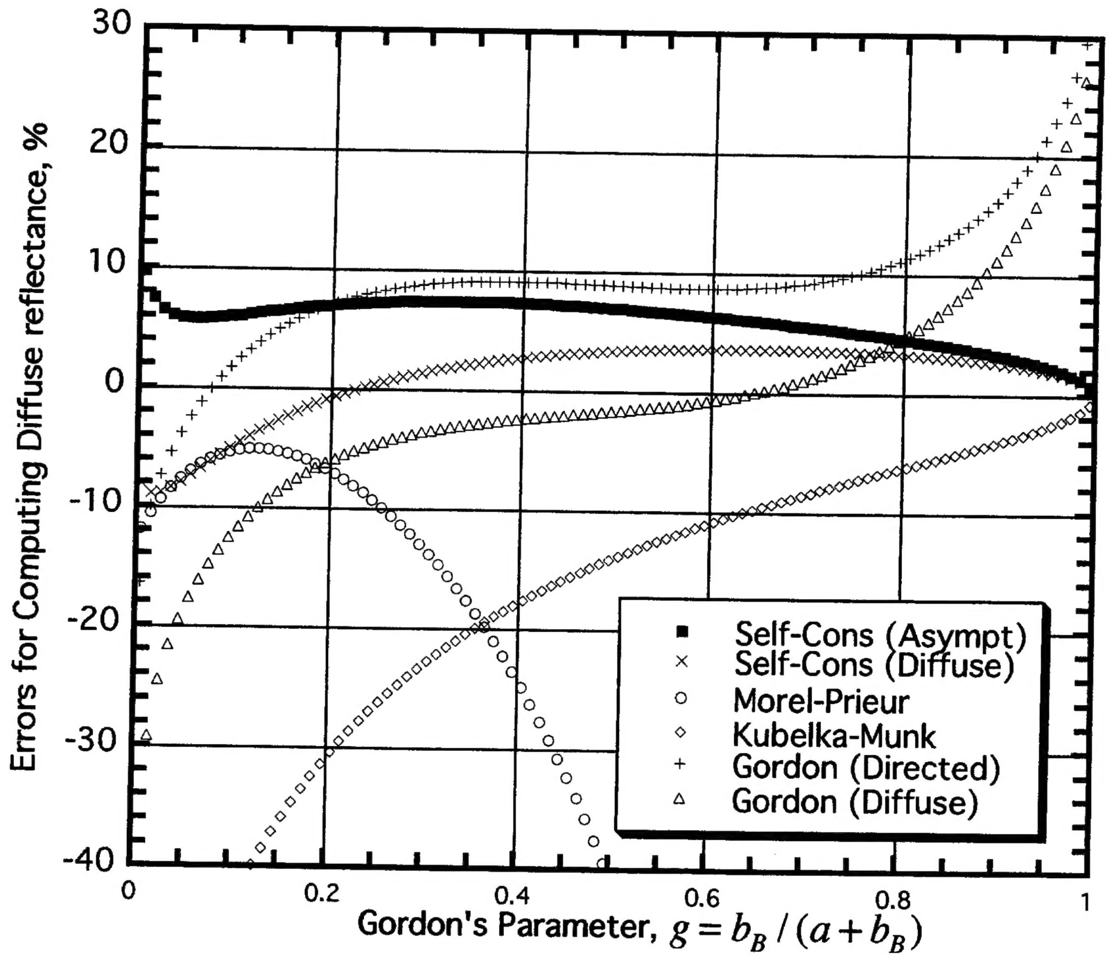

Figure 3. Error distribution for various equations to compute diffuse reflectance.

4. Conclusion

The use of linear Eq. (9) is restricted to open ocean waters and coastal waters with $g \leq 0.1$. Equation (10) is not adequate for clean ocean waters, and Eqs. (11)-(12) are good only for typical ocean waters excluding very turbid and extremely clean waters [12]. In order to maintain 10% accuracy for the whole range of variability of optical properties of seawater we should use nonlinear Eqs. (1), (2), (4), and (5). The choice of equation should depend on the problem involved because they are related to the different theories.

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12. The defect in Eqs. (11)-(12) consists of non zero values at $g = 0$ due to the formal use of regression analysis. The initial unpublished data of Ref. [9] is good for the case of extremely clear water too.